

# Chiral d-wave superconductivity in the heavy-fermion compound CeIrIn<sub>5</sub>

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**Abstract.** - Recent thermal conductivity measurements in the heavy-fermion compound CeIrIn<sub>5</sub> indicate that its superconducting order parameter is very different from CeCoIn<sub>5</sub>. Here we show that these experiments are consistent with chiral d-wave symmetry, i.e.  $\Delta(\vec{k}) \sim e^{\pm i\phi} \cos(ck_z)$ .

The discovery of antiparamagnon mediated superconductivity in the 115 heavy-fermion compounds CeTIn<sub>5</sub>, where T represents Co, Ir, Rh, or a mixture of these, has recently opened up a new avenue to unconventional nodal superconductivity [1]. These strongly interacting materials are characterized by a plethora of competing ground states in addition to superconductivity, including conventional and unconventional spin density wave (SDW) phases [2]. Among the 115 compounds, the currently most well studied is CeCoIn<sub>5</sub> for which a d-wave superconducting order parameter  $\Delta(\vec{k}) \sim \cos(2\phi) = \hat{k}_x^2 - \hat{k}_y^2$  has been identified [3–6]. Indeed, there are many parallels between CeCoIn<sub>5</sub> and the high- $T_c$  cuprates, including (a) a layered quasi-two-dimensional Fermi surfaces [7], (b) d-wave superconductivity, and (c) d-wave spin density wave order in the pseudogap phase [8–10].

Recent thermal conductivity measurements [11, 12] indicating an order parameter symmetry in CeIrIn<sub>5</sub> very different from the one in CeCoIn<sub>5</sub> came as a big surprise. An initial analysis of this data suggested a hybrid  $E_g$  gap,  $\Delta(\vec{k}) \sim Y_{2,\pm 1}(\theta, \phi)$ , based on the assumption that the Fermi surface is three-dimensional. However, the Fermi surface of CeIrIn<sub>5</sub> is in fact quasi-two-dimensional, as known from band structure analysis [7, 12]. Therefore, one needs to consider instead superconductivity in layered structures, similar as discussed in Refs. [13, 14]. In this case, only  $f = e^{\pm i\phi} \sin(\chi)$  (chiral d-wave) with  $\chi = ck_z$  or  $f \sim \sin(\chi)$  (non-chiral p-wave) are consistent with the observed thermal conductivity data [11]. The magnitudes of the d-wave and chiral d-wave/non-chiral p-wave order parameters  $|\Delta(\vec{k})|$  are shown in Fig. 1.

In the following, we present a theoretical analysis based on a generalized BCS model that properly accounts for a quasi-two-dimensional Fermi surface and a chiral d-wave superconducting order parameter. The thermal conductivity is computed following the recipe given in Refs. [14, 15]. Here, we assume for simplicity that the quasiparticle scattering is due to impurities. Furthermore, we consider the physically relevant limit  $\Gamma/\Delta \ll 1$ , where  $\Gamma$  is the quasiparticle scattering rate in the normal state and  $\Delta (= 0.856K)$  is the maximum value of the energy gap at  $T = 0K$ . This  $\Delta$  is the weak-coupling value for nodal

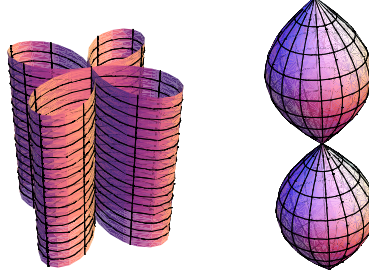


Fig. 1: Magnitude of order parameters  $|\Delta(\vec{k})|$  for d-wave (left) and chiral d-wave/non-chiral p-wave (right) superconductors.

superconductors [13, 16].

Let us begin by considering the zero-temperature limit. For quasi-two-dimensional structures, the thermal conductivity strongly depends on the direction within the material. Therefore we will discuss the cases  $\vec{q} \parallel \vec{a}$  (in-plane) and  $\vec{q} \parallel \vec{c}$  (out-of-plane) separately. Here  $\vec{q}$  denotes the heat current. For  $\vec{q} \parallel \vec{a}$ , one obtains

$$\frac{\kappa^a}{\kappa_n^a} = \frac{2\Gamma_a}{\pi\Delta} \quad (1)$$

and similarly for  $\vec{q} \parallel \vec{c}$

$$\frac{\kappa^c}{\kappa_n^c} = 2 \left( \frac{\Gamma_c}{\Delta} \right)^2, \quad (2)$$

where  $\Gamma_a$  and  $\Gamma_c$  denote the in-plane and out-of-plane scattering rates respectively. Eq.1 describes the universal heat conduction as discovered by P. Lee [17, 18], whereas Eq.2 is very different. The strength of the impurity scattering can be extracted directly from the experimental data show in Fig. 2 of Ref. [11], from which we can deduce that  $\frac{\Gamma}{\Delta} = 0.19635$ . Furthermore, from the observed anisotropy of the thermal conductivity, we can infer the ratio of the Fermi velocities along the c-axis and the a-b plane, i.e.  $\frac{v_c}{v_a} = 0.66$ , which is very similar to  $\frac{v_c}{v_a} = 0.5$  extracted for CeCoIn<sub>5</sub> [8]. Then, for  $T \neq 0K$  but  $\frac{T}{\Delta} \ll 1$ , we obtain in the regime  $T \gg \Gamma$ ,

$$\frac{\kappa^a(T)}{\kappa_n^a(T)} = \frac{27}{2\pi^2} \zeta(3) \left( \frac{T}{\Delta} \right) + O \left( \frac{T}{\Delta} \right)^3, \quad (3)$$

and

$$\frac{\kappa^c(T)}{\kappa_n^c(T)} = \frac{45^2}{4\pi^2} \zeta(5) \left( \frac{T}{\Delta} \right)^3 + O \left( \frac{T}{\Delta} \right)^5. \quad (4)$$

This is consistent with the experimental observation of a dominant in-plane heat conductivity proportional to the temperature, and a subdominant out-of-plane conductivity.

In order to connect these finite-temperature results with the above equations for  $T = 0$ , we use an interpolation formula which applies in the regime for  $T/\Delta(T) \ll 1$ . The resulting low-temperature thermal conductivities are then given by

$$\frac{\kappa^a(T)}{\kappa_n^a(T)} = \frac{2\Gamma_a}{\pi\Delta} \left( 1 + \left( \frac{27}{4\pi} \zeta(3) \frac{T}{\Gamma_a} \right)^2 \right)^{1/2} \quad (5)$$

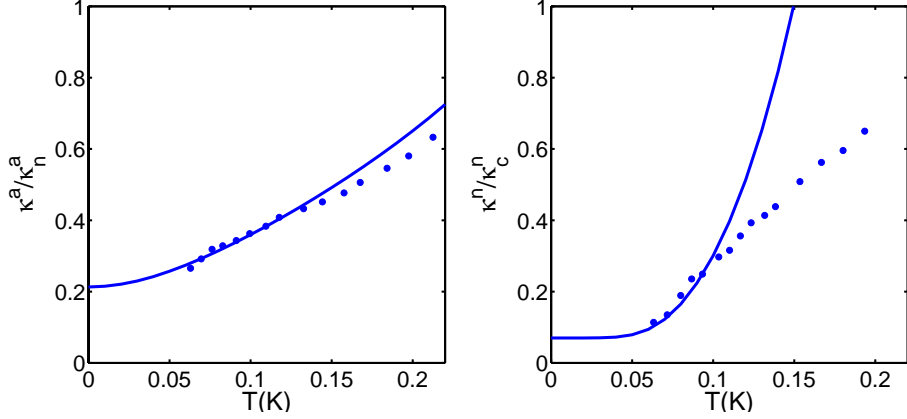


Fig. 2: Thermal conductivity in the  $\vec{q} \parallel \vec{a}$  (in-plane) and  $\vec{q} \parallel \vec{c}$  (out-of-plane) directions.  $T_c = 0.4K$ . The symbols represent experimental data from [11], and the solid lines are low-temperature fits using Eqs. 5 and 6.

and

$$\frac{\kappa^c(T)}{\kappa_n^c(T)} = 2 \left( \frac{\Gamma_c}{\Delta} \right)^2 \left( 1 + \left( \frac{45^2}{8\pi^2} \zeta(5) \left( \frac{T}{\Gamma_c} \right)^2 \left( \frac{T}{\Delta} \right) \right)^2 \right)^{1/2} \quad (6)$$

respectively.

In Fig. 2, we compare these dependencies with the experimental data reported in Ref. [11]. A fit of the low-temperature regimes yields good agreement with  $\frac{\Gamma_c}{\Gamma_a} = 0.5592$ . Evidently, the quasi-particle scattering rate is somewhat anisotropic in the present system. Here, the temperature dependence of the gap function  $\Delta(T)$ , is approximated by

$$\Delta(T) = 2.14T_c \left[ 1 - \left( \frac{T}{T_c} \right)^3 \right]^{1/2} \quad (7)$$

with  $T_c = 0.4K$ , which is known to be a very good approximation for d-wave superconductors [19].

Similarly, the ratio  $\kappa^c(T)/\kappa^a(T)$  can be computed and compared to the experiments. Within our model, it is given by

$$\kappa^c(T)/\kappa^a(T) = 0.2703 \left[ \frac{1 + \left( \frac{45^2}{8\pi^2} \zeta(5) \right)^2 \frac{T^6}{\Gamma_c^4 \Delta^2}}{1 + \left( \frac{27}{4\pi} \zeta(3) \right)^2 \left( \frac{T}{\Gamma_a} \right)^2} \right]^{1/2} \quad (8)$$

which is shown in Fig. 3 along with the thermal conductivity measurements of Ref. [11].

These expressions give a very reasonable description of the thermal conductivity for  $T/T_c \leq 0.3$ . We note that a similarly good description of the thermal conductivity is given by the hybrid gap proposed in Ref. [11]. At higher temperatures,  $T/T_c \geq 0.3$ , our simple model fails to describe the measured thermal conductivity, possibly due to the fact that phonons begin to play an important role as we approach  $T \rightarrow T_c$ . Nevertheless, we can conclude that chiral d-wave SC is consistent with the experimental data of Refs. [11, 12] in the relevant low-temperature regime. Note also, that our calculations predict an interesting upturn in the ratio  $\kappa^c(T)/\kappa^a(T)$  as the temperature is further lowered. This prediction can

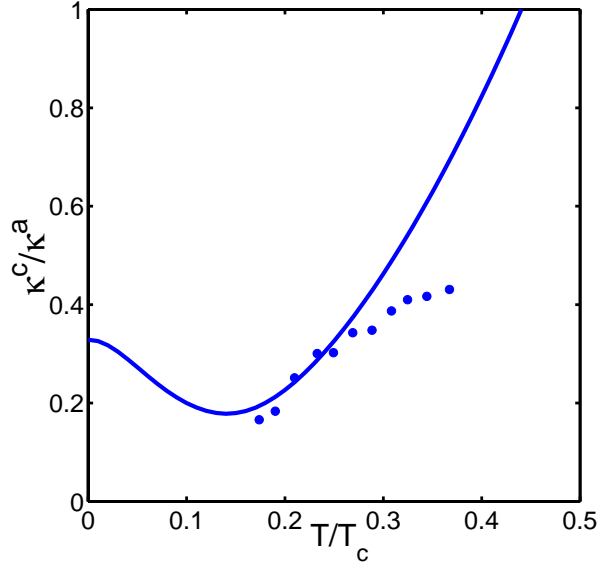


Fig. 3: Ratio of thermal conductivities of the  $\vec{q}||c$  and  $\vec{q}||\vec{a}$  direction, plotted as a function of  $T/T_c$ . The symbols represent the experimental data from Ref. [11].

be scrutinized experimentally, and may serve as a means to distinguish the present theory from the hybrid gap model that was proposed earlier.

In the present context, the unconventional superconducting order in  $\text{CeRhIn}_5$  is of great interest. Let us briefly contemplate on the doped case. Inspecting Fig. 3 of Ohira-Kawamura et al [12] we may conclude that the order parameter in  $\text{CeRh}_{1-x}\text{Co}_x\text{In}_5$  should be d-wave SC with an angular dependence  $f = \cos(2\phi)$ , whereas the order parameter in  $\text{CeRh}_{1-x}\text{Ir}_x\text{In}_5$  is consistent with chiral d-wave superconductivity with an angular dependence  $f = e^{\pm i\phi} \cos(\chi)$ . Therefore, the above approach will provide a basis to identify the many competing phases of the 115 compounds. Also, the phase diagrams for  $\text{CeRh}_{1-x}\text{Co}_x\text{In}_5$  and  $\text{CeRh}_{1-x}\text{Ir}_x\text{In}_5$  in Ref. [12] are of great interest for the perspective of the Gossamer superconductivity, i.e. a phase with competing order parameters [10,20,21]. We observe that (a) the incommensurate phases in both  $\text{CeRh}_{1-x}\text{Co}_x\text{In}_5$  and  $\text{CeRh}_{1-x}\text{Ir}_x\text{In}_5$  are conventional spin-density waves, (b) the commensurate phase in  $\text{CeRh}_{1-x}\text{Co}_x\text{In}_5$  and the incommensurate+commensurate phase in  $\text{CeRh}_{1-x}\text{Ir}_x\text{In}_5$  have d-wave symmetry. Therefore, there is a wide region where d-wave superconductivity coexists with unconventional nodal spin density wave order.

In summary, we have successfully applied a nodal weak-coupling BCS theory to fit recent experimental data on the directional thermal conductivity of  $\text{CeRhIn}_5$ . We find that in contrast to  $\text{CeCoIn}_5$ , which has plain d-wave order, this compound is consistent with chiral d-wave superconductivity. Furthermore, this technique will allow us to identify the many different phases which were recently discovered in doped derivatives of these materials.

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